Int. J. Oral Maxillofac. Surg. 2014; xxx: xxx–xxx
http://dx.doi.org/10.1016/j.ijom.2014.07.013, available online at http://www.sciencedirect.com

International Journal of Oral & Maxillofacial Surgery

Review Paper
Trauma

Wound ballistics of firearm-related injuries—Part 1: Missile characteristics and mechanisms of soft tissue wounding

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P. K. Stefanopoulos, K. Filippakis, O. T. Soupiou, V. C. Pazarakiotis: Wound ballistics of firearm-related injuries—Part 1: Missile characteristics and mechanisms of soft tissue wounding. Int. J. Oral Maxillofac. Surg. 2014; xxx: xxx–xxx. © 2014 International Association of Oral and Maxillofacial Surgeons. Published by Elsevier Ltd. All rights reserved.

Abstract. Firearm-related injuries are caused by a wide variety of weapons and projectiles. The kinetic energy of the penetrating projectile defines its ability to disrupt and displace tissue, whereas the actual tissue damage is determined by the mode of energy release during the projectile–tissue interaction and the particular characteristics of the tissues and organs involved. Certain projectile factors, namely shape, construction, and stability, greatly influence the rate of energy transfer to the tissues along the wound track. Two zones of tissue damage can be identified, the permanent cavity created by the passage of the bullet and a potential area of contused tissue surrounding it, produced mainly by temporary cavitation which is a manifestation of effective high-energy transfer to tissue. Due to the complex nature of these injuries, wound assessment and the type and extent of treatment required should be based on an understanding of the various mechanisms contributing to tissue damage.

Keywords: Wound ballistics; Gunshot wounds; Missile injuries; Ballistic injuries; High-energy missile trauma.

Accepted for publication 21 July 2014

''Dans les champs, le hasard ne favorise que les esprits préparés'' (In the field [of observation], chance favours only the prepared mind)

Louis Pasteur

The wounding power of firearms is an important issue in penetrating trauma, both war and civilian,[1–6] and as such it may also affect surgeons with little knowledge or concern about weapons and their effects. The study of these effects produced by missiles has been termed 'wound ballistics',[7] indicating its subordination to the science of projectile motion. In this context, the term missile implies small projectiles capable of tissue penetration because of their energy rather than their shape.[8] Wound ballistics examines the relationship between the properties of the missile and the severity of the resultant wound, and the role of the various mechanisms of ballistic penetration in the production of tissue damage.[9] These aspects apply to battle casualties, the majority of which are caused by munition fragments rather than bullets,[1,10–13] as well as to ballistic injuries seen during peacetime.

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Please cite this article in press as: Stefanopoulos PK, et al. Wound ballistics of firearm-related injuries—Part 1: Missile characteristics and mechanisms of soft tissue wounding, *Int J Oral Maxillofac Surg* (2014), http://dx.doi.org/10.1016/j.ijom.2014.07.013

In both of these environments, the maxillofacial region represents a prominent location for missile injuries,[14–17] but it is mainly due to civilian firearm violence that this area often appears as an intentional close-range target, whether the consequence of assault or suicide attempt.[18–21] In the face, the close anatomical relationship of soft and hard tissues results in a complex pattern of firearm-related injuries,[22] with comminution of bone and teeth as a common feature.[23,24] Furthermore, the amount of non-viable tissue following ballistic trauma remains a critical concern, especially when primary reconstructive procedures are contemplated.[18,25,26] Although the assessment of the unique consequences of these injuries is a subject of surgical judgement, an understanding of wound ballistics can provide the basis for interpretation of the mechanism of tissue damage with respect to its extent along the wound track; in this way the surgeon is also prepared for potential complications.[25–28] In this paper, the first of two, we present the wounding effects of small arms projectiles on soft tissue. In the second part, the pathophysiology and ballistic aspects of maxillofacial missile injuries are discussed.

Wounding agents

Firearm-related injuries among the civilian population are commonly inflicted by handguns, rifles, and shotguns.[18,29,30] These weapons are included under the military term 'small arms',[31] and are generally defined by their type and calibre (diameter).

Handguns and rifles

Both handguns and rifles are rifled firearms. Rifling is an important feature of all firearms except shotguns, indicating a series of spiral parallel grooves cut into the bore (the inner surface of the barrel).[18,29–35] Calibre refers both to the diameter of the bore and the bullet maximum diameter.[36–38] It is expressed either as a decimal fraction of an inch (with the nought in front of the decimal point usually omitted) to designate American and British weapons and cartridges,[29,31,37–39] or in millimetres based on the metric designation system,[29,38–40] which is the standardized method for sizing military ammunition.[31,35,38]

Handguns are of two major types, revolvers and auto-loading pistols. They are the most frequently used type of firearm in civilian conflicts.[6,18,31,41,42] Common handgun calibres range from .22 to .45 in. (Fig. 1). The more rarely encountered submachine guns are truly automatic weapons typically using handgun ammunition.[31,33]

Rifles are the most powerful of the commonly encountered small arms,[31,41,42] and they are categorized into two main classifications, those for military use, called assault rifles, and the hunting rifles.[42,43] Assault rifles use ammunition of smaller calibre than most handguns and are capable of firing either single shots (semi-automatic fire) or in bursts (fully automatic fire) through the use of a selector level. Most renowned are the Russian AK-47 (Kalashnikov; calibre 7.62 mm) and the American M16 (calibre 5.56 mm). Civilian versions of assault rifles, such as the AR-15 edition of the M16, normally lack the fully automatic mode.[42]

Fig. 1. Examples of pistol ammunition. From left to right: .38 Super; 9-mm Luger; .40 Smith & Wesson (S&W); .45 Automatic Colt Pistol (ACP). The former two are essentially of the same diameter, but the .38 Super is more powerful as indicated by its considerably longer cartridge case containing larger propellant charge. Note also the truncated 'semiwadcutter' (SWC) configuration of the .40 S&W compared to the more common round nose shape of the other bullets. (One cent coins are shown for comparison.).

Ammunition

The cartridge (round of ammunition) is the functional unit of firearm ammunition, renewed for each firing. The bullet is the part of the cartridge that hits the target and does not refer to a complete round of ammunition. The round consists of the cartridge case containing the propellant ('powder'), with the bullet mounted on the open end of the case and the primer incorporated into the opposite closed end (base or head).[18,30,31,37,44]

Combustion of the powder ignited by the primer produces rapidly expanding gases which propel the projectile out of the cartridge case and down the barrel of the gun.[37] During its acceleration, the bullet attains two types of motion simultaneously, forward translation and also rotation on its longitudinal axis (spin) as it encounters the grooves of the rifled bore (Fig. 2).[44] Spinning serves to gyroscopically stabilize the bullet during its flight, thus increasing both its range and accuracy.[3,31,33,34,36,43–46]

Most bullets are composed primarily of a lead alloy, but lead-free (non-toxic) metallic bullets are also available.[31,38] Bullets are either solid or jacketed. Jacketed bullets have a core of lead or mild steel covered by a coating (jacket) of a harder metal, such as cupronickel or a steel alloy,[30,31,36,38,39] and they come in two basic constructions.[47] Partially jacketed (semi-jacketed) bullets have the tip either simply left exposed ('soft-point') or hollowed out ('hollow-point'); they typically flatten or 'mushroom' when striking soft tissue with sufficient velocity,[31,48] hence they are known as expanding bullets. Full metal jacketed (FMJ) bullets, also known as 'ball ammunition', have the jacket enclosing the tip to prevent it from such deformation.[22,31,38,41–43,47,49] Rifle bullets are jacketed in order to prevent the soft lead core being stripped and deposited in the rifling at the high velocities accomplished.[31,47]

An unfortunate term for expanding bullets is 'dum-dum'.[48] It essentially refers to a modification of the official military FMJ .303 British rifle bullet, made for the British Indian Army in 1897 at the Dum-dum arsenal near Calcutta. That

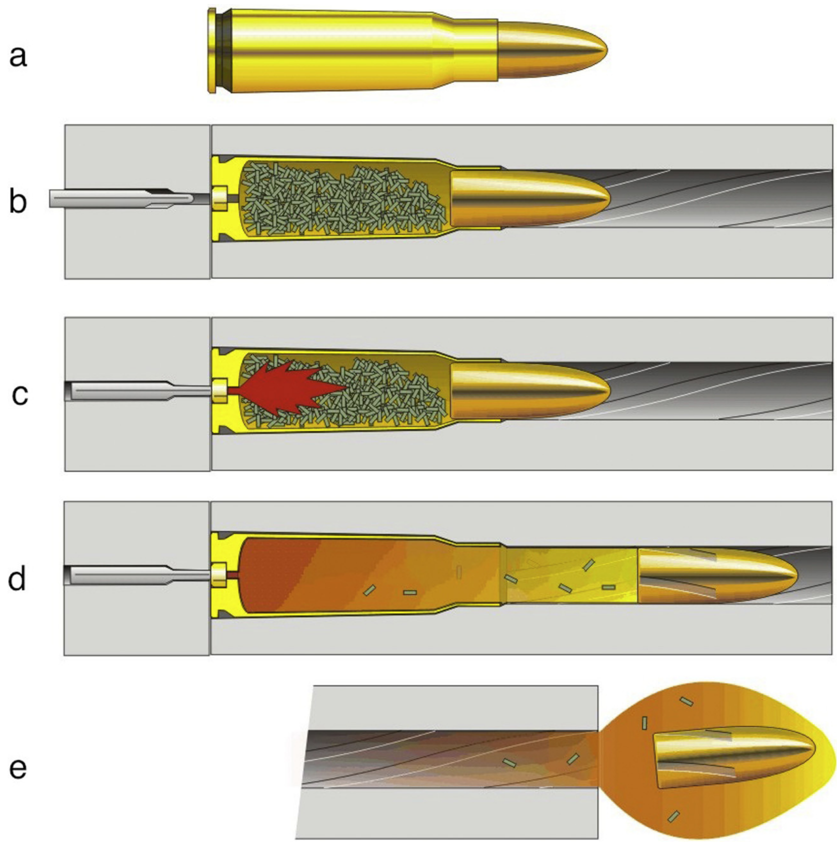

Fig. 2. Artistic drawing of a rifle cartridge, (a) intact and (b) in the gun chamber just before firing with the cartridge case cut across to demonstrate the primer and propellant powder. (c) The irreversible firing process activates the firing pin which serves to strike the primer, the latter producing a minute explosion. (d) This ignites the powder generating the propellant gases, which accelerate the bullet down the barrel, while at the same time it attains rotation (spin) as it encounters the rifled bore. (e) During the exit from the muzzle, slight deviation of the body of the bullet from its axis of flight occurs.
Reproduced from Ref. 37, courtesy of Professor Jorma Jussila.

bullet had its jacket opened at the tip with 1 mm of the lead core exposed[50] in order to deform and thereby produce greater wounding effect.[40,51–55] For humanitarian reasons, any similar expansible construction has been banned by the Hague Convention of 1899,[51–60] and FMJ ammunition has become the standard form allowed for military purposes (Fig. 3).[35,36,51,54,58]

Where soft-point and hollow-point bullets are legitimately in use by civilians, the former type is most popular for hunting rifles and the latter for handguns (Fig. 4).[31] Newer designs of hollow-point handgun bullets that mushroom more consistently have been introduced, such as the Hydra-Shok and the 9-mm Luger bullets Blitz-Action-Trauma (BAT) and Action 4.[22,31,38] Handgun ammunition containing small pellets is also commercially available, releasing them either within the barrel or upon impact with the target, as with the Glaser Safety Slug.[31,36,42,48,61]

The generic suffix ‘Magnum’ implies an increased amount of propellant loaded in a longer case than standard cartridges.[31] The term is not specific to a larger calibre as commonly believed. The .357 Magnum (Fig. 5) introduced in 1935 was based on the .38 Special cartridge, actually of the same bullet diameter, but it provides nearly double the velocity and more than three times greater muzzle energy than the standard .38 Special loads.[40] Magnum also refers to heavy-frame firearms specifically chambered for Magnum cartridges.[29]

Shotguns

Shotguns have a smooth bore, the diameter of which is designated by gauge rather than calibre, with the exception of the .410 calibre.[31,62–64] In general, the higher the gauge number, the smaller the barrel diameter.[31,64] Shotguns fire either multiple pellets or a single large projectile called a slug.[30,31,62–64] Pellets are contained within the shotgun cartridge called a shell, and are collectively known as the shot (Fig. 6)[63]; their number depends on their size and the gauge of the gun.[62] Magnum shotgun shells contain more propellant and a heavier charge of shot (more pellets).[31] In general, pellets range in diameter from 1 to 10 mm, falling into two major categories, the more common birdshot, which refers to smaller shot size, and buckshot.[31,42] Wadding, commonly in the form of a plastic insert, is used to isolate the shot from the propellant and prevent it from rubbing against the inner wall of the barrel.[31,38,64]

Shot charge and wadding are the components that leave the muzzle upon firing,[61,62] following which the shot expands and lengthens.[38] The distribution of pellets, referred to as pattern,[63] is effectively determined by the choke, a constriction of the bore at the muzzle end of the barrel.[31,40,62]

Wound ballistics

The physics of the motion of projectiles are classically described under a number of sections. Internal (interior) ballistics deals with the acceleration phase within the gun barrel, being applicable to missiles fired from barrelled weapons.[10] External (exterior) ballistics studies the flight of the projectile through air, whereas terminal ballistics studies the behaviour of projectiles during penetration of solid materials.[7,9,10,24,31,45,65–67]

Wound ballistics is a term originally used by Callender and French[68] to introduce a special branch of terminal ballistics, which addresses the effects of projectiles on living tissues, either animal or human, or on tissue simulants.[7,66,69,70] These effects are determined by a number of factors, both projectile- and tissue-related. Upon impact, various properties of the missile combine to create disruptive forces producing tissue damage (Table 1); the retentive forces by which tissue strives to retain its integrity react against these factors.[3,7,67] This projectile–tissue interaction represents the central event in ballistic tissue penetration,[1,71] as it is only during this process that certain features of the projectile, mainly related to its construction and design, which largely determine its terminal behaviour, become apparent.[34,45]

Wounding power and wounding effects

The tissue damage that a bullet is capable of represents its wounding power, also

Fig. 3. Examples of military rifle ammunition, identified by calibre and cartridge case length, both in millimetres. From left to right: 5.56 × 45 mm NATO, used in the M16 rifle; 7.62 × 39 mm Russian (Kalashnikov) used in the AK-47 rifle; 7.62 × 51 mm NATO; 7.62 × 54 mm (Rimmed) (Mosin–Nagant); .30-06 Springfield (7.62 × 63 mm) used in the M1 Garand rifle, also a very popular hunting cartridge in the USA.

referred to as the wounding potential.[72] It is related to two basic ballistic parameters, mass and velocity.[72–76] As a function of these parameters, the kinetic energy possessed by the projectile at impact is thought to provide the best estimate of wounding power.[18,34,43] This widely accepted theory has led to the common misconception that the tissue damage produced can be adequately predicted in terms of the familiar kinetic energy (KE) formula (KE = $\frac{1}{2}mv^2$), with emphasis placed on the velocity component (v) as it enters the equation raised to the second power. This, however, represents an oversimplification,[5,8] since it does not take into consideration the projectile–tissue interaction.[12,66,75,77]

Muzzle velocity is the maximum velocity of the bullet as it leaves the muzzle,[10,29,74] while the impact (striking) velocity is the one recorded when the bullet hits the target. Whereas velocity decreases with distance according to the laws of external ballistics,[74,78] in most civilian wounds inflicted at close range, the impact velocity can be considered approximately equal to the muzzle velocity, which can be found published in ballistic charts.[29]

Projectiles are loosely classified into ‘low-velocity’ and ‘high-velocity’ categories,[8,35] which roughly correspond to muzzle velocity characteristics of handguns and rifles, respectively.[5,28,73] Military rifles typically have muzzle velocities that exceed 700 m/s, whereas those delivered by conventional handguns are in the range between 250 and 370 m/s. Accordingly, as pointed out by Kneubuehl,[61] the commonly used distinction between ‘low-velocity’ and ‘high-velocity’ bullet wounds serves, if at all, only as a form of general differentiation between wounds caused by handguns and rifles. Rifle bullets cause certain effects, mostly related to a significantly larger amount of energy imparted to tissues, that are almost undetectable with conventional handgun bullets.[28,61,79] The clinical implication is that ‘high velocity’, generally defined as exceeding 600 m/s,[45] is considered synonymous to the most severe missile injuries, relating the specific character of the wound to the speed of the penetrator.[8,80,81] However, current thinking suggests that the impact velocity can be misleading as the sole indicator of the extent and severity of the inflicted wound,[1,18,35,57,76,77,82] although it influences other factors that may have overall greater effect upon the wounding process.[56,83] Furthermore, mass is also important, as a heavier missile better maintains its speed in flight due to its higher inertia, and is potentially more damaging for a greater penetration depth in tissue compared with a lighter one with the same or even higher impact velocity.[9,34,45]

The kinetic energy of a penetrating projectile constitutes the only available amount of energy for work to be performed within tissue[70]; however, it is only the energy delivered to tissue itself that can result in wound production.[5,8,34,38,81,82,84–86] Consequently, thinking in terms of kinetic energy absorption provides a working knowledge of the extent of the resultant tissue damage,[34,87] as the former has been proved a physically consistent means of explaining damage that occurs both locally and at some distance from the projectile path,[88] as well as a measure of wound comparison.[89] Based on these premises, the current classification of ballistic injuries into those produced by either ‘low-energy’ or ‘high-energy’ transfer is more appropriate than previous classifications defined by the type of weapon or its power.[1,11,45,57,70,82,87]

The descriptive term ‘high-energy missile trauma’,[55] in particular, refers to the

Fig. 4. 9-mm Luger hollow-point cartridge (middle), compared to two full metal jacketed cartridges, of the same calibre (left) and .45-calibre (right). Note the manufacturer’s scoring of the jacket around the hollowed tip to facilitate expansion.

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Fig. 5. .357 Magnum jacketed soft point (JSP) revolver cartridge. Note the characteristic longer case containing high power loading.

Table 1. Projectile factors involved in wound ballistics.

Inherent ballistic properties
Mass: determines kinetic energy, inertia, penetration capacity
Calibre: normally of lesser importance; large calibres increase wounding effects
Kinetic ballistic properties (conferred by the weapon)
Velocity: determines kinetic energy, penetration capacity, drag
Kinetic energy: determines overall wounding power
Factors affecting drag profile and stability in tissue
Shape (round nose versus pointed 'spitzer' nose; boat-tail versus flat base)
Construction (full-jacketed versus semi-jacketed; location of centre of mass)
Length

ballistic wound pattern produced by a substantial quantity of kinetic energy. Although some authors regard 400 J as the cut-off between low- and high-energy deposition into tissues,[32] it is important to understand that the designation 'high-energy' is used in this context to define the wounding effect rather than the amount of energy used up.[55,82,90,91] Nevertheless, in quantitative terms, a 'high-energy' wound results from a typical assault rifle bullet at velocities between 600 and 1000 m/s, depending on range. In such a case, the net amount of energy deposited into tissues will vary from one hundred to a few hundred Joules and in exceptional cases up to thousands.[82]

However, the human body is not a homogeneous target, and the local effects induced by a missile also depend to a large extent on the viscoelastic properties of the various tissues,[4,7,45,73,83] which may react in different ways to missiles of the same size and velocity.[12,57] Although the damage produced appears to be proportional to the amount of energy delivered to the tissue, the conception of energy transfer by penetrating projectiles entails an understanding of the mechanisms of tissue disruption that is effected, rather than viewing the latter simply as the end result of random dissipation of kinetic energy.[1,34,91] It should also be remembered that it is the proximity of the wound to vital organs that ultimately determines the severity and outcome of the injury.[72]

Factors affecting the efficiency of energy transfer: the projectile–tissue interaction

When a bullet comes to rest within the body without deforming or losing its substance, its entire kinetic energy has been transferred into the tissues,[8,45,92,93] whereas when such a bullet perforates through the body, only part of its energy is used up in wound formation.[12,31,46,86,93] In either case, the energy transferred is not always uniformly distributed along the wound track, nor is the resultant tissue damage,[45,78,84,87,94,95] a fact most evident when an enlarged exit wound is opened.[84,96] This is because, in addition to the different properties of the tissues, there may also be variations in the behaviour of the bullet itself along its path,[87,91] as demonstrated by terminal ballistics in homogeneous tissue simulants, such as gelatin and soap.[1,34,55,84] Therefore, besides the energy possessed by a penetrating projectile, what is important for the extent of wounding is the rate of energy loss in transit through the target tissue.[97] This is determined by drag, which is the force causing the retardation of the projectile.[1,8,9,45,70,98] Impact kinetic energy and drag can be considered the two main descriptors of the projectile–tissue interaction, which results in energy transfer to tissue.[45]

Drag (F_D) is expressed in terms of the density of the surrounding medium (ρ), the cross-sectional area of the projectile presented onto a plane perpendicular to its motion (presenting or frontal area, A), and its velocity (v), according to the equation $F_D = ½C_D\rho Av^2$, where C_D is the drag coefficient.[45,55,99–101] Because of the exponential effect of velocity on drag, the kinetic energy loss in tissue will be much greater with high-velocity missiles.[45] At supersonic speeds, this effect becomes critically important, hence the 'spitzer' (pointed) contour of the forebody in modern military rifle bullets (Fig. 3), which affects the C_D in such a way that a very large drag is avoided.[44]

However, the most complex implications occur due to changes in the presenting area of the projectile.[99] Whereas spherical missiles facilitate experimental

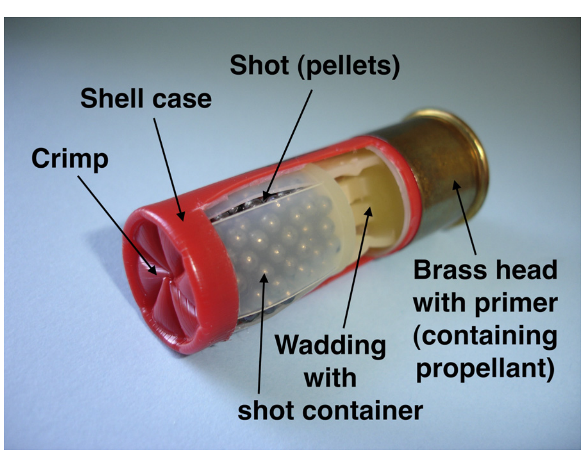

Fig. 6. 12-gauge shotgun shell (opened).

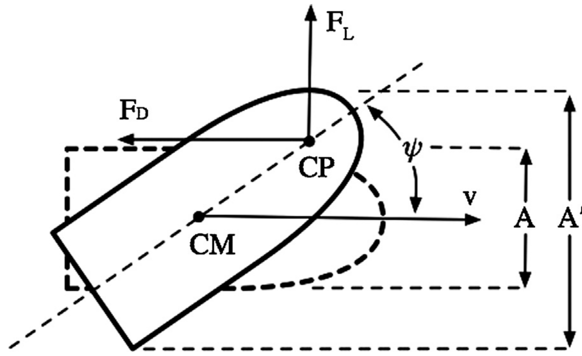

Fig. 7. Drawing of a yawing bullet with its centre of mass (CM) and centre of pressure (CP). The bullet in a point-on orientation is depicted in the background (dashed line). Distances *A* and *A′* represent the presenting area of the projectile in flight, point-on (*A*) and at yawing (*A′*). F_L = lift vector; F_D = drag; v = velocity vector coincident with the axis of flight; ψ = angle of yaw (exaggerated).

purposes as they offer a constant presenting area,[33,92,102] bullets are designed to afford the minimum area of presentation with the maximum possible mass by their elongated body,[74,89] which introduces the factor of stability to their movement.[1,45,46,67,85] A stable bullet is one travelling 'nose-on' with its axis always close to its trajectory described by its centre of mass.[34,55] When this axis deviates from the tangent to the trajectory, the bullet's presenting area can only increase. This deviation is called yawing, expressed as the angle of yaw.[29,33,44,45,81]

Yawing occurs around the bullet's centre of mass.[72] A tendency to yaw is inherent to all bullets flying nose-on,[45,49,68,103,104] without representing instability,[105] exaggerated immediately after the exit from the muzzle due to the destabilizing effects of the muzzle vibrations and the outburst of propellant gases.[44,55,81,104,105] Available data for military weapons suggest that, at this point, the maximum angle of yaw is of the order of 5°–6° (Fig. 2e).[89,103] Any such deviation generates lift-induced drag, which concentrates on the so-called centre of pressure of the bullet, located in front of its centre of mass. As a result, an overturning moment, most prominent in spitzer bullets, is created, which tends to destabilize the projectile (Fig. 7).[33,38,45,99,101,106] This effect is gyroscopically counteracted by the high rate spin imparted by rifling.[34,44–47,49,81,107] Spin stabilization, however, is not instantaneous, as the spin induces other variations in motion on a yawing bullet.[45,46,56,100,103,108] As a consequence, the bullet nose describes in space a spiral of declining amplitude, which in its simplest form is known as precession,[29,33,44,45,81,104,108] similar to the wobbling of a spinning top knocked sideways.[34,38,81,100] Within a distance of 100 m, precession is damped and the bullet flies virtually nose-on.[38,46,49,81,89,105]

However, once the bullet enters the body it cannot maintain its previous orientation because the stabilizing action of spin is overcome by tissue density exceeding that of air by approximately 800 times or more[33,45,47,55,56,72,89,109]; as soon as yawing begins, the overturning moment will further increase the angle of yaw by a positive feedback.[45,70] A spin-stabilized bullet becomes unstable if yaw exceeds approximately 15°,[38] and eventually it will tumble as the angle increases beyond 90°.[1,56,106,108,110] Given an adequate distance of tissue penetration, tumbling appears as an integral part of the ballistic behaviour of modern military rifle bullets,[55,77,84,106] following which they may continue travelling with reversed orientation presenting their base in front (Fig. 8).[45,54,70,72] In the literature, tumbling is often overused as synonymous to excessive yawing.

Yaw in tissue has a major influence on the wounding process[105] because it involves a greater projectile area contacting and severing more tissue.[1,29,33,34,45,55,70,77,96] As the bullet approaches 90° of yaw, its entire length acts to effect tissue disruption in the extreme,[47] resulting in maximum energy transfer.[1,29,91,96] As a result, a rifle bullet traversing soft tissue sideways at velocities above 600 m/s is also subjected to overwhelming stresses, which may cause flattening of the cylindrical body and even break-up of the jacket, depending on the bullet's construction.[45,70,109,111,112] The latter typically occurs at the level of the cannelure (a circumferential recess on the jacket into which the mouth of the cartridge case is crimped), with subsequent extrusion of the lead core.[35,45,70,112]

Bullet fragmentation, once considered only the result of bone hits,[68] gained considerable medical attention following early reports from the Vietnam War,[113,114] which mentioned tumbling of the M16 rifle bullet as an additional cause for its excessive wounding effects, previously attributed solely to its high velocity (about 940 m/s).[74,75,77] It was revealed that fragmentation of that bullet secondary to tumbling in soft tissue follows a characteristic pattern,[115] being the major wounding factor associated with its ballistic behavior.[45,73,77,96] Previous experience from Northern Ireland also suggested an extensive nature of the wounds produced by the M16 rifle and its civilian version AR-15.[80,116]

Bullet fragmentation is widely regarded as the culmination of the projectile–tissue interaction, which enhances the dynamics of the penetrating trauma because the fragments produce multiple lacerations around the main wound track.[34,80,96,117] However, a retrospective analysis of a large series of war wounds from the Red Cross database[58] concluded that bullet fragmentation is an unreliable indicator of wound severity, as it was present in only 7.9% of 'large' wounds, whereas it may also occur with less extensive injuries. The low incidence of this finding in 'large' wounds must be correlated to the

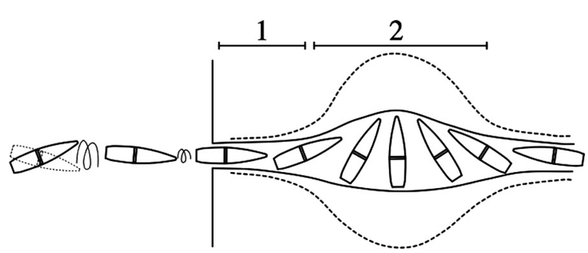

Fig. 8. Idealized ballistic performance of a military rifle bullet in air and through tissue. The bullet penetrates tissue from left to right. The wound track displays an initial narrow channel or neck (1), but subsequently widens owing to bullet yawing and tumbling (2). The temporary cavity causes radial expansion of the wound track in a spindle-shape fashion, outlined at its maximum by the dashed line. Note that bullet tumbling, shown here within a short distance for illustrative purposes, normally requires a certain penetration depth. Note also the declining precession of the bullet in air, which intensifies upon entering tissue.

fact that most current designs of military rifle ammunition, including the AK-47 bullet of Russian origin and the current standard NATO M16 rifle bullet, do not fragment unless they strike a large bone.[45,72,115] The association of bullet fragmentation with as much as 3.5% of those wounds not defined as 'large'[58] is less clear; since most of the examined wounds affected the limbs,[58] the results may have been influenced by bone hits resulting in bullet break-up with less severe fractures that did not meet the criteria for 'large' wounds. For bullet fragmentation to occur, an additional amount of kinetic energy is spent, which is dissipated to the bullet itself rather than to the tissue.[86] Furthermore, when associated with bone impact, this finding exhibits different energy transfer characteristics than when occurring in soft tissue, not necessarily indicating high-energy transfer (Fig. 9).

Unjacketed lead bullets fired from handguns usually do not break up, owing to their low velocity, although they may deform, particularly if bone is struck (Fig. 10).[5] Expanding bullets that deform to a mushroom shape attain a much greater surface area of presentation. This results in higher energy loss early in the projectile path[6,30,118,119] and a much greater amount of tissue crushed compared to that from a non-deforming projectile travelling nose-on.[43,75] Expanding bullets do not yaw because mushrooming offers shoulder stabilization.[70]

In general, increasing velocity enhances the penetration capacity of the projectile,[9,34,45] but this is straightforward only up to the point where the also increasing drag forces begin to affect its form.[120] Subsequent deformation reduces its penetration potential in proportion to the resultant widening of its presenting area,[6,43,120] but also because part of its kinetic energy is used in the deformation process.[53,58,86] Because of this effect, a handgun bullet that mushrooms tends to be arrested within tissues, giving up all its energy, and this is the rationale for the use of expanding bullets in police weapons to reduce the risk of injured bystanders following over-penetration of the intentional target.[22,61] On the other hand, a non-deforming rifle bullet can pass through a narrow target without significant yaw, thus producing a low-energy-transfer wound despite its high-velocity impact.[8,45]

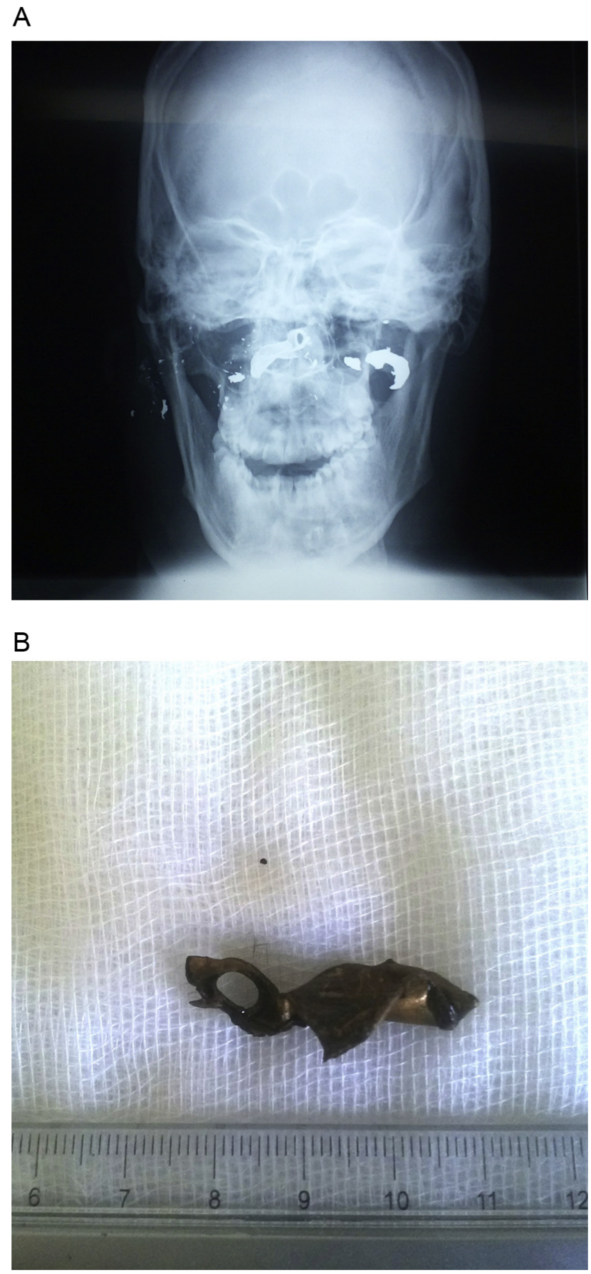

Fig. 9. Fragmentation of a military rifle bullet following impact with the right malar eminence, which also had a dramatic effect in altering its trajectory (the bullet was removed through the pharyngeal wall). The wound was sustained in a war zone, with much of the bullet's kinetic energy spent as a result of an apparently distant shot, which explains the absence of significant bone injury. At radiograph (a), the jacket can be distinguished from the separated lead core (far right) by its open base resembling a hoop, a typical manufacturing characteristic of FMJ bullets. The jacket opened both at the level of cannelure and longitudinally (b).

Mechanisms of firearm-related injuries

During ballistic penetration of the human body, effective energy transfer produces direct as well as indirect tissue damage.[9,45,80] The importance and magnitude of each of these effects are determined by the characteristics of the projectile and the tissues involved.[73]

Direct injury, sometimes called prompt damage,[18,121] occurs as penetration is accomplished by a process of rapid distension followed by rupture of tissue by the projectile's leading edge, resulting in tissue laceration surrounded by contusion.[8,49] In the case of low-energy wounds, such tissue damage is largely confined to the wound track,[5,28,57,81] minimizing the need for debridement.[4,32] However, when a projectile penetrates at high velocity, extremely high hydrodynamic pressures develop in the immediate vicinity,[122–125] producing a more substantial crushing component of direct tissue damage.[82,124] Moreover, two other highly

Please cite this article in press as: Stefanopoulos PK, et al. Wound ballistics of firearm-related injuries—Part 1: Missile characteristics and mechanisms of soft tissue wounding, *Int J Oral Maxillofac Surg* (2014), http://dx.doi.org/10.1016/j.ijom.2014.07.013

Fig. 10. Deformed handgun lead bullet retrieved transorally from the right masseteric area of a police officer. The deformation was due to impact upon the ipsilateral mandible.

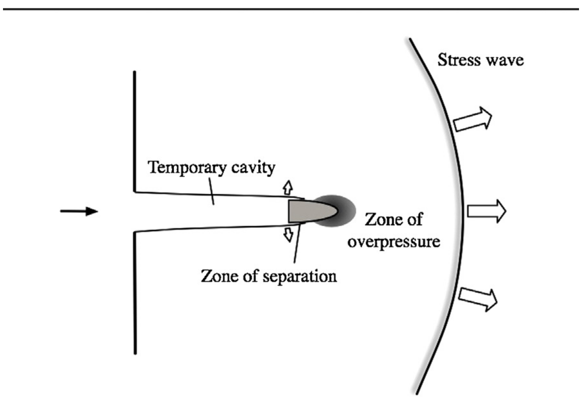

Fig. 11. Pressure phenomena set off by a bullet penetrating tissue at high velocity: at the point of impact, a stress wave is formed, which rapidly spreads ahead without actual tissue movement; secondarily, separation at the projectile–tissue interface results in temporary cavity formation behind the bullet.

dynamic pressure phenomena appear (Fig. 11),[9,70,122,126,127] responsible for indirect injury without contact between tissue and projectile.[1,45,57,80]

Initially, a pressure wave of roughly spherical form propagates from the very point of impact forwards, with approximately the velocity of sound in water (1500 m/s), thus leaving the retarded projectile behind.[9,46,55,61,70,81,122,123] Although often considered as a shock wave, this is more properly referred to as stress wave[1,5,11,45] or ballistic pressure wave.[97] Despite their intensity,[9,61,70,122] the ability of stress waves to cause tissue injury has been disputed,[1,5,35,75,77,128] based on their short duration and the lack of tissue movement or macroscopic tissue damage.[122] However, bursts of stress waves of much longer duration have been recorded in live animal models,[129] associated with reflection and diffusion of the primary disturbance by heterogeneous body parts.[9,45,61,123] By this mechanism, susceptible interfaces of differing acoustic impedance can be damaged,[11,130] accounting for the capillary endothelial and blood–brain injury previously reported in animals.[129] More recent research suggests that stress waves may induce microscopically apparent damage to the nervous system,[131] particularly to the brain.[132,133] Probably of greater importance in causing cell damage are the concomitant abrupt changes between high positive and negative pressures.[61,92]

In a second phase, the previously static tissue is forced to detach itself at some point from the surface of the advancing projectile by flow separation.[55,99] This phenomenon, which is characteristic of flow past an object that is not sufficiently streamlined, becomes conceivable when the tissue material is viewed as ‘flowing’ backwards with respect to the projectile. Because of the existing pressure gradients,[92,130] separation rapidly proceeds to expansion of the wound track, which may be out of proportion to the bullet’s dimensions, culminating into what is known as a temporary wound cavity.[9,33,55,70,122,123] This important biological effect has the potential for inflicting injury beyond the confines of the wound track,[1,35,55,75] considered the main mechanism whereby high-energy missile wounds are produced.[46,49,57,70,123]

Temporary cavitation

The formation of a cavity of transient character by the projectile[134,135] is a dynamic process of very short duration, involving radial tissue displacement associated with secondary pressure changes.[55,61,70,122,127,130,136] This is considered the result of momentum imparted to soft tissues particles, which are then accelerated en mass at right angles to the direction of its trajectory creating a void.[9,11,33,45,55,65,122] The cavity significantly lags behind the missile due to the inertia of the tissues displaced,[45,46,53,80–82,108,134,135] reaching maximum size within approximately 1 ms after its passage.[9,45,89] Thereafter, tissue elasticity causes the cavity walls to pulsate in a violent waning fashion and eventually collapse,[9,33,45–47,55,134] hence the name temporary cavity.[67,81]

The maximum volume of the temporary cavity is related to the amount of kinetic energy transferred by the projectile in combination with the elastic properties of the tissues,[1,9,55,137,138] whereas its cross-sectional area at any given point depends on the local drag force.[55,92,137] The relationship of cavity volume to the energy expended has been demonstrated by Harvey et al.[9] by means of two spheres of different masses fired through the thighs of cats; with striking velocities adjusted so that measured energy losses were approximately the same for both spheres, the volumes of the temporary cavities produced were approximately equal.

Cavitation is to some extent a feature of almost all missile wounds,[5,6,81,134,136,139] but its clinical significance depends on the size of the cavity and, most importantly, the characteristics of the tissue involved.[75] The temporary cavities induced by low-velocity bullets are not large enough to cause significant injury except in sensitive tissues,[72] particularly the brain.[140–143] Cavity formation becomes clinically important usually at striking velocities exceeding 300–600 m/s, beyond which the cavitation changes become much more marked.[45,80]

The mechanism of tissue damage by cavitation is usually summarized as radial stretching[66,77]; it may extend over a wide area subjected to peripheral compression by the expanding cavity, also involving shearing effects related to tissue

heterogeneity.[3,7,66,73,75] Inelastic organs such as the liver are far more susceptible to disruption than skeletal muscle,[7] which can tolerate better the cavitation effects as long as there is no circulatory impairment or uncontrolled infection.[5,34,77,78,81] Within the confines of the skull, the pressure built up due to cavity formation by rifle bullets is usually devastating for the brain.[11,46,49,66,127] With projectiles penetrating at very high velocities, the skull bones may be blown apart.[9,31,46,66,70] Such an explosive effect is not seen on empty skulls, indicating the necessity of a medium with fluid properties for the development of high-pressure phenomena.[9]

Projectile shape, construction, and stability play a greater role in determining both the size and location of the temporary cavity than velocity alone.[45–47] Modern military type rifle bullets appear to cause minimal disturbance in tissue as long as they are travelling nose-on, due to their low drag profile.[47,55,75,85,137,144] However, their tendency to yaw has a dramatic effect on cavitation because of the separation phenomena induced by a yawing bullet.[99] Accordingly, the peak of the temporary cavity produced by a non-deforming bullet is not close to the entrance where it still has highest velocity, but rather at the point where it turns sideways.[1,34,47,55,96] Large temporary cavities in animal wounds have been reported with small-calibre military ammunition from the M16 rifle, attributable to a combination of high velocity and bullet tumbling.[96]

The penetration distance before the yaw cycle commences corresponds to an initial segment of the wound track, termed narrow channel or neck,[66,70,109] which is demonstrable in tissue simulants preceding cavity expansion (Fig. 8).[1,54,55] The length of the narrow channel differentiates the performance of various military rifle bullets,[1,60,106] as it is a measure of the bullet's stability in soft tissue, which in turn affects its wounding effect.[96,115] This distance typically varies between 15 and 25 cm,[35,54,75,109] but it is considerably shorter for the M16 as well as the newer Russian AK-74 rifle bullets.[75,96]

A recent study[145] raised doubts about the universal validity of these estimations, which are based on the measured residual deformation of gelatin[111,146] and soap ballistic models.[54,70] Using flash X-ray radiography, the authors demonstrated large irregular temporary cavities in human cadaver thighs penetrated through muscle by two types of military rifle bullets. They also reported that cavitation by 7.62-mm bullets occurred in the absence of significant yawing, although they did not provide measurements of the projectile path.[145] However, because of the strong dependence of bullet yawing and the resultant energy transfer on wound channel length, this quantity must be accurately measured when flash X-ray imaging is used, especially where considerable variation is expected.[33,86] In addition, cadaveric soft tissue may not adequately reflect the cavitational changes occurring in the living.[70] Nevertheless, the differences in cavitation phenomena observed in humans or animals from those developed in tissue simulants are currently an active area of research.[99,147]

With expanding bullets, the temporary cavity displays a different pattern. These bullets are associated with almost immediate cavitation without a narrow channel component, because of the deformation resulting in maximum drag and energy transfer at an early point.[6,54,70,118] The cavity produced is also markedly increased in size,[47,49,54] and a deforming bullet from a powerful handgun may produce localized 'high-energy' effects, comparable to those seen with the much faster assault rifle bullets.[6,82] An FMJ bullet that has ricocheted becomes unstable, also creating a temporary cavity immediately after impact.[70]

Vascular damage from temporary cavitation can be extensive. Capillaries and small blood vessels are mainly affected, resulting in areas of focal bleeding.[9,49,80,81,122,135] Large vessels not severed by the bullet tend to escape gross injury as they are pushed aside due to their elasticity,[9,49,81,108,135] although endothelial injury and thrombosis may still occur.[4,5,45,94,108] However, even large arteries may be torn apart by the stretching mechanism.[10,148] Nerve trunks stretched by cavitation without breaking may lose function, usually temporarily.[9,41,45,81,135]

When cavitation is associated with missile or bone fragmentation, the result is usually severe.[5,96] Bullet fragmentation causes lacerations susceptible to subsequent disintegration by the stretching of the temporary cavity.[69,117,149] This synergistic mechanism of tissue disruption may account for the creation of large exit wounds by high-velocity projectiles.[47]

Shotgun injuries

The severity of shotgun injuries is determined by the range and the shot pattern.[31,32,62,64,93] At close range (less than 3 m), the shotgun produces the most devastating injuries of all small arms,[25,28,31,41,72,150] because the pellets are still tightly clustered, without significant reduction of their muzzle velocity of 350–400 m/s.[72,93] Under these circumstances, the wound appearance is primarily determined by gauge rather than pellet size, as the entire shot tends to function as a single large missile.[23,72,93,151] At ranges up to 7 m, wadding material should also be suspected to be lodged in the wound as radiolucent foreign bodies.[11,23,62,64,72,93]

Because of their non-aerodynamic shape, the spherical pellets slow rapidly in flight and their wounding capacity drops significantly with distance,[31,63,93] whereas the shot also spreads out[62,63] causing multiple discrete wounds determined by the pellet size.[32,62] Beyond 10–12 m, superficial wounds are usually inflicted,[11] and clothing may further reduce the penetration capacity of individual pellets.

Shotgun slugs produce massive internal injuries within a range of 100 m, comparable in severity to those encountered from hunting rifle bullets.[31,32,63] Temporary cavities play no significant role in shotgun injuries except for those inflicted by slugs.[31,32]

Pathological and morphological characteristics of bullet wounds

The visible or palpable wound track produced by a bullet is known as the permanent wound cavity. It consists of a wound of entrance and, if the projectile has perforated the body, a wound of exit.[73] Accordingly, the wound may be penetrating ('blind') or perforating ('through-and-through').[23,150]

In skeletal muscle, the permanent cavity is surrounded by an area of cellular and endothelial damage,[95] the gross appearance of which is that of bruised tissue.[149] Microscopically this area of contusion, also known as the zone of extravasation,[5,89] contains haemorrhagic, non-viable tissue bearing the typical histopathology of necrotic myocytes,[45,82,95] the innermost layer of which may eventually slough becoming part of the permanent cavity.[45,149,152] The contusion zone is surrounded by a ''concussion zone'' characterized by grossly normal muscle with histological evidence of potentially reversible damage.[45,82,95] In brain injuries, the contusion zone roughly corresponds to an inner zone of astrocyte destruction surrounded by a bleeding zone; a wider outer oedematous area is marked by axonal and neuronal injury.[142,153]

Bullets are not sterilized by the heat of firing; they carry bacteria from the gun barrel, clothes, skin, and mucosal surfaces into the wound,[35,81,94,154–157] which subsequently colonize tissue. An important aspect of temporary cavitation is the active

Table 2. Summary of bullet behaviour in tissue.

Bullet type	Penetration capacity	Yawing/tumbling	Fragmentation	Mushrooming	Temporary cavitation
Non-deforming (FMJ)					
Handgun	Great	Limited yawing	No	N/A	Small to moderate cavity
Rifle	Over-penetration	Tumbling	After bone impact[a]	N/A	Large cavity, maximum at 90° of yaw
Expanding					
Handgun	Limited	No	After bone impact	Yes (with sufficient velocity)	Moderate to large cavity near entrance (coincident with mushrooming)
Rifle	Over-penetration	No	At high velocities or after bone impact	Yes	Very large cavity near entrance (coincident with mushrooming)

FMJ, full metal jacketed; N/A, not applicable.
[a] Fragmentation occurs in soft tissue with some lead core copper-jacketed military rifle bullets at striking velocities above 700–900 m/s.[111,117]

contamination of the wound by foreign material aspirated through the entrance and, if present, the exit site, owing to the sub-atmospheric pressure within the expanding cavity.[34,81,155–158] Furthermore, shearing effects of cavitation may separate tissue planes[149] allowing the spread of contamination.[159] This results in a large amount of dead tissue inoculated with bacteria and debris from the surface, which represents the specific pathology of the high-energy missile injury.[46,55]

Tissue disruption and damage are most extensive where energy transfer has been greatest, which is close to the entrance for non-aerodynamic projectiles, while with non-deforming bullets this occurs deeper within the wound, concurrent with yaw growth.[96,144,152,160] Perforating wounds by military rifle bullets in the hind legs of anesthetized animals have been shown to heal uneventfully in the absence of bony and major vascular damage,[78] provided that free drainage of necrotic tissue is established through the exit wound.[161] On a microscopic level, necrosis appears to progress for up to 6 h after wounding, following which inflammatory changes and possibly infection predominate.[152] These observations indicate that, unless heavily contaminated, well-perfused muscle surrounding the wound track remains largely viable. This includes uncomplicated soft tissue wounds inflicted by modern military rifle bullets, thereby requiring only minimal wound excision.[34,82,162,163] However, ischaemia may contribute to a more prolonged course of tissue necrosis, in addition to the delayed effects of the initial trauma.[80,164]

The permanent wound cavity, presumably the most important aspect of wounding,[41,125,165] is mainly the result of tissue crushing[111] rather than tissue expelled. Its size increases by any supervening bullet expansion, yawing or fragmentation,[111,116,166] but it is also influenced by the magnitude of the preceding temporary cavity depending on the elastic recoil of the tissues.[45,81,82] The effect of bullet calibre in soft tissue wounding has little importance from a surgical point of view.[35,80] Expert opinion suggests that the wounds produced by handgun bullets of various types usually cannot be differentiated at autopsy[119]; this may not apply to wounds caused by larger bullets, such as the .45 calibre, for which moderately greater wounding effects in animal tissue have been reported.[78]

The external appearance of the gunshot wound may be one of three general types.[162,167] The typical entrance wound consists in a punctate-type circular defect approximately the same diameter as the bullet. The second type of wound is characterized by a stellate appearance created by skin splits but not tissue loss. The third type of wound is the avulsive injury characterized by tissue loss, usually produced by close-range shotgun blasts.

Military rifle bullets invariably exit the body, except when fired from a distance.[18,31,43,61] Although a stellate exit wound indicates high-energy transfer as a result of temporary cavity expansion near the exit site,[10,55,82,96,138,152] the less common scenario of a punctate exit wound does not necessarily suggest the opposite, particularly in the case of a long wound track, which may conceal a deeper area of serious tissue disruption.[1,13,55,75,138] Sometimes, handgun injuries may also present with larger and irregular exit wounds, most likely due to bullet tumbling.[10,18,31,116] Expanding rifle bullets produce massive injuries with enormous exit wounds.[31,43]

In conclusion, the current classification of missile injuries into low-energy and high-energy ones correlates the degree of tissue damage with the amount of energy transferred by the penetrating missile. Although the velocity of the projectile is a major determinant of its striking kinetic energy, the proportion of that energy resulting in wound production is determined by the degree of retardation of the projectile, influenced by its presenting area and the density of the target tissue. Expanding bullets undergoing deformation upon impact, and non-deforming bullets, generally offer two different models of energy transfer based on their drag profile (Table 2). High-energy ballistic trauma is characterized by substantial tissue damage beyond the wound track created by the projectile, as a result of the formation of a large pulsating temporary cavity, which also contributes to wound contamination. These wounding effects, however, are of lesser extent compared to the distinctively massive injuries produced by shotgun blasts.

Funding

None.

Competing interests

None.

Ethical approval

Not required.

Patient consent

Not required.

Acknowledgements. The authors would like to thank their colleague Mr. Demetrios Gyftokostas for his assistance in the

section on wounding mechanisms, and Professor Norman M. Rich for providing important but not readily accessible literature references based on his experience with the management of combat injuries. We are particularly grateful to Professor Bo Janzon for providing a copy of his doctoral dissertation and to Dr. Chris Giannou for kindly agreeing to review the manuscript.

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Please cite this article in press as: Stefanopoulos PK, et al. Wound ballistics of firearm-related injuries—Part 1: Missile characteristics and mechanisms of soft tissue wounding, *Int J Oral Maxillofac Surg* (2014), http://dx.doi.org/10.1016/j.ijom.2014.07.013